Proceedings of the Institute of Acoustics

MUTUAL COUPLING IN MULTI-CHANNEL LOUDSPEAKER SYSTEMS

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1. INTRODUCTION

In a recent paper [1], the authors showed how the reproduction of phantom stereo images is usually compromised by the interference between the output from the two loudspeakers and the consequent low frequency mutual coupling effect. In this paper, the concepts explained in [1] are extended to include multi-channel loudspeaker systems such as used for surround sound in cinema and home cinema systems. In most modern stereo recordings, much of the important information-carrying sounds, such as lead vocals and instruments, narration or dialogue, are panned centrally between the loudspeakers, so phantom images are very important. Although it is less common for all four (or more) loudspeakers in a surround sound system to be asked to reproduce the same signal, the potential for mutual coupling problems to occur between each possible pair of loudspeakers as well as between all loudspeakers at once is very great.

The influence of room boundary walls on the power output of a loudspeaker has been well researched and documented. In [2], Allison shows how the presence of a single boundary wall increases the power output of a loudspeaker by 3dB at low frequencies, and that introducing two more boundaries gives a net increase of 9dB. More recently, Ward and Angus [3] have extended the concept further to include all six boundary walls. The significance of these findings in the context of this paper is that the presence of a single boundary gives rise to the same sound field as would the introduction of a second, identical loudspeaker placed at the mirror-image position in the absence of the wall. It is therefore logical to assume that introducing a second, identical real loudspeaker – the second of a stereo pair – would also increase the power output of the first loudspeaker. However, whereas the influence of room boundaries on loudspeaker power output is signal independent and may be predicted and corrected for by loudspeaker design and / or electrical equalisation, the influence of one loudspeaker on the other in a stereo pair is *very* dependent upon the exact nature of the (independent) signals fed to the two loudspeakers. For example, when a stereo pair of loudspeakers is reproducing a fully left- or fully right-panned signal, only one loudspeaker is operating, so, 'perfect' sound reproduction is possible. For centrally-panned images however, both loudspeakers are receiving the same signal, and interference effects give rise to a sound field that is very dependent on position and frequency. These problems are compounded when four or more independent loudspeakers are in use.

2. MUTUAL COUPLING THEORY

The concept of mutual coupling between loudspeakers is familiar to anyone who has mounted two loudspeakers close together. The power output of the two loudspeakers is approximately four times (+6dB) that of a single loudspeaker. Also, if you double the area of the diaphragm of a loudspeaker drive-unit, given the same diaphragm velocity, the power output will again increase by 6dB. What is perhaps less obvious however, is how introducing a *distant* second loudspeaker can double the power output of a loudspeaker. In order to explain mutual coupling it is desirable to consider perfect loudspeakers operated under ideal acoustic conditions. In the analysis that follows, the loudspeakers are considered to be compact pulsating spheres which operate as constant-velocity-sources; a model that fairly accurately represents many real loudspeakers at low frequencies.

2.1 Multiple Loudspeakers in a Reflexion-Free Environment

Consider a single, perfect, omnidirectional, velocity-source loudspeaker (loudspeaker A) in an anechoic chamber; the frequency response of the loudspeaker is the same everywhere (flat). Now introduce a second perfect loudspeaker into the anechoic chamber (loudspeaker B) and feed it with the same signal as the first. The response is no longer flat everywhere because of the interference between the sound fields radiated by the two loudspeakers – the combined output is no longer omnidirectional. At all positions in the chamber, the two radiated sound fields constructively or destructively interfere depending on the path length differences and the wavelength (frequency) of the sound – resulting in a comb-filtered response. Along a thin centre-line equidistant from the two loudspeakers, however, a flat response 6dB higher in level than that of one loudspeaker alone is observed. The combined sound field can be calculated as the sum of the pressures generated by the two loudspeakers, and this pressure can be compared to that generated by a single loudspeaker of the same output, placed midway between the pair:

$$\frac{p_2}{p_1} = \frac{R}{r_A} e^{-jk(R-r_A)} + \frac{R}{r_B} e^{-jk(R-r_B)} , \qquad (1)$$

where R, r_A and r_B are the distances from the point of interest to the central loudspeaker, loudspeaker A and loudspeaker B respectively and $k = \omega / c_0$ is the free-space wavenumber at an angular frequency of ω radians per second. Figure 1 shows the frequency response of a pair of loudspeakers, spaced 3m apart, at two typical positions away from the centre-line, relative to that of a single loudspeaker placed midway between the pair. Figure 2 shows the far-field directivity of the loudspeaker pair.

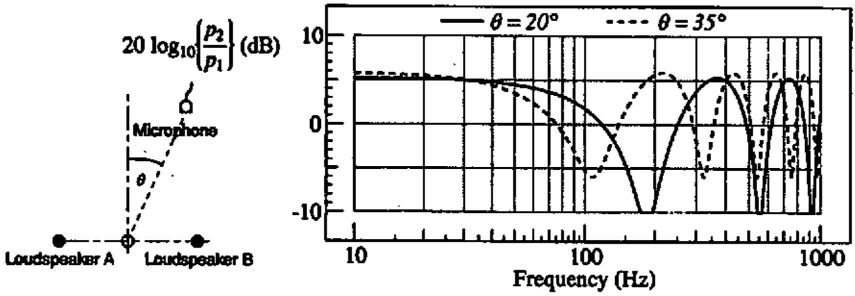

Figure 1 Combined Frequency Response of a Stereo Pair of Omnidirectional Loudspeaker at Two Different Angles from the Centre-Line in an Anechoic Chamber Relative to that of a Single Loudspeaker Placed Mid-Way Between the Two – Loudspeaker Separation 3m – Loudspeaker Radius 0.15m – Microphone 3m from point mid-way between loudspeakers

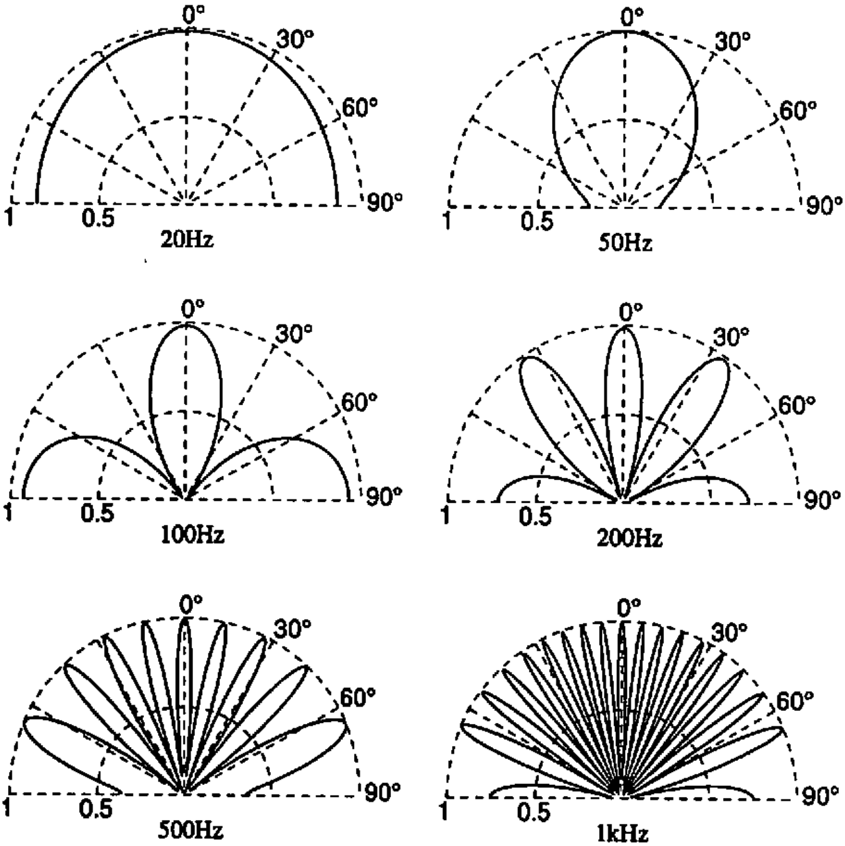

Figure 2 Combined Far-Field Directivity of the Loudspeaker Pair in Figure 1

The introduction of more loudspeakers into the anechoic chamber gives rise to more complicated interference patterns. Figure 3 shows the frequency response of four loudspeakers, arranged in a rectangle of 3m × 4m, at two points within the rectangle. It should be noted that a flat response will only be observed at a point in the centre of the rectangle.

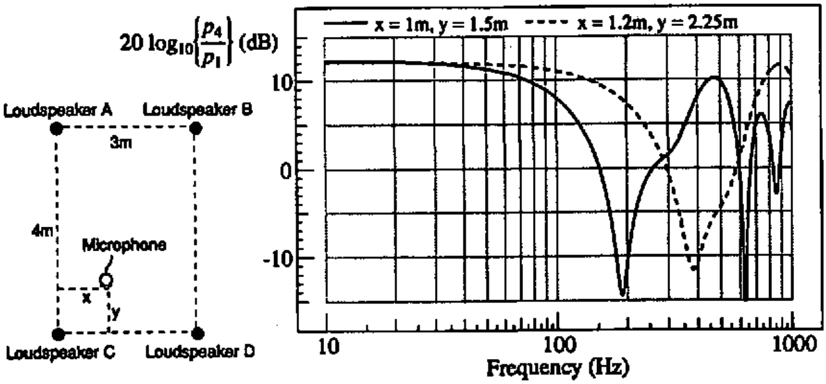

Figure 3 Combined Frequency Response of Four Omnidirectional Loudspeakers at Two Different Positions in an Anechoic Chamber Relative to that at the Centre due to a Single Loudspeaker

2.2 Multiple Loudspeakers in a Highly Reflective Environment

In a perfect reverberation chamber, the frequency response of a single loudspeaker at any point is the sum of an infinite number of reflexions from the walls, all of which arrive with different time delays (a diffuse field). The reverberant response therefore depends upon the total power output of the loudspeaker, and is thus the same (almost) everywhere. The power output of any source can be found by integrating the anechoic responses over all angles, so the frequency response of an omnidirectional loudspeaker in the reverberation chamber is the same as in the anechoic chamber (this is a hypothetical situation however, as the continuous radiation of *any* acoustic power into a perfect reverberation chamber would give rise to infinite sound pressures).

The power output of a pulsating sphere can be written

$$W = \frac{S}{2}\,\Re\{p(a)\,u(a)^*\} \ , \tag{2}$$

where a is the radius of the sphere, $u(a)$ is the surface velocity of the sphere, $p(a)$ is the acoustic pressure on that surface, S is the surface area, $\Re\{\}$ denotes the "real part of" and * denotes the complex conjugate. For a pair of velocity-source loudspeakers, $u(a)$ is fixed and $p(a)$ is the sum of the pressure generated by loudspeaker A due to its own velocity and that generated by loudspeaker B on the surface of A. As shown in [1], the combined power output of the pair of loudspeakers, relative to that of a single source is then

$$\frac{W_2}{W_1} = 2\left(1 + \frac{a}{d}\cos\big(k(d-a)\big) + \frac{1}{kd}\sin\big(k(d-a)\big)\right) \approx 2\left(1 + \frac{\sin(kd)}{kd}\right) \text{ if } (d \gg a) \ , \tag{3}$$

where d is the distance between the two sources. Figure 4 shows the combined power output of a pair of velocity-source loudspeakers relative to the power output of one of the loudspeakers operating in isolation.

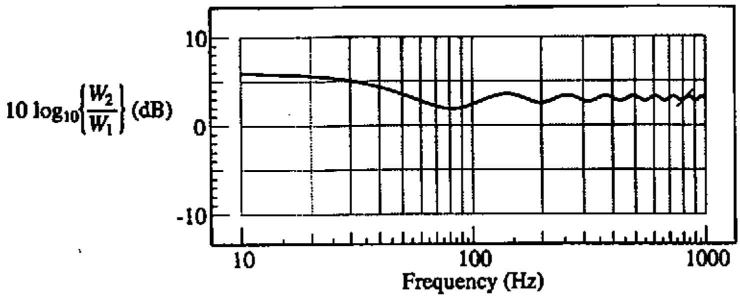

Figure 4 Combined Sound Power Output of the Pair of Loudspeakers in Figure 1 Relative to that of a Single Loudspeaker

The important features to note about figure 4 are that, in agreement with [2] for a single loudspeaker and reflective wall, at high frequencies the power output of the pair of loudpeakers is approximately +3dB (double) relative to that of a single loudspeaker – entirely as expected, and that at low frequencies the increase in power output is nearer +6dB (four times). The "magic" doubling of power output at low frequencies is due to mutual coupling, which results from the superimposition of the output of the two loudspeakers at all angles (see figs 2 and 3).

Figure 5 shows the combined power output of the four loudspeakers in figure 3 relative to one of the loudspeakers operating in isolation.

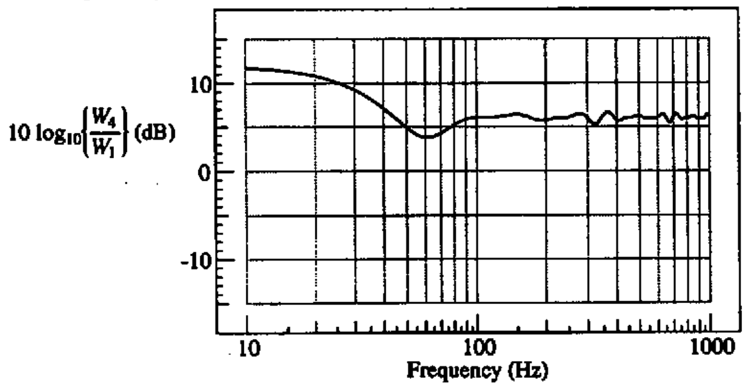

Figure 5 Combined Sound Power Output of the Four Loudspeakers in Figure 3 Relative to that of a Single Loudspeaker

It is clear from figure 5 that each of the loudspeakers is coupled with each other loudspeaker to yield a +12dB (16 times) power increase at low frequencies; the increase being approximately 6dB at higher frequencies.

3. DISCUSSION OF PRACTICAL IMPLICATIONS

The analysis above concentrates on ideal loudspeakers operated in ideal acoustic environments. What is of interest is how this behaviour translates to the operation of multiple real loudspeakers in actual listening environments. By making the assumption that real rooms have acoustic properties that lie somewhere between the two extremes of anechoic and fully reverberant, it can be concluded that the response at any position within a real room will be a combination of the summation of the direct (anechoic) sounds from the loudspeakers and some function of the total radiated power. Clearly, the relative importance of the direct and reverberant sound fields, and hence mutual coupling, depends upon the position in the room and upon any acoustic treatment of the room; ie. how close the room is to either anechoic or reverberant.

What the above results also show is that the problems with phantom images in non-anechoic rooms are not due to an increase in low frequency output relative to a single loudspeaker, but rather an effective decrease in mid- and high-frequency output as a consequence of interference.

3.1 Timbre of the Panned Image

When multiple loudspeakers are operated in a non-anechoic room, the response at any point within the room will depend upon the number of loudspeakers that are simultaneously radiating the same signal. For example, If a sound is (amplitude) panned from one loudspeaker across to another, there will be a change in timbre of the sound from relatively 'flat', when one loudspeaker is operating, through 'coloured', as mutual coupling increases the low-frequencies in the centrally panned image relative to mid- and high-frequencies, and back to flat when only the second loudspeaker is operating. The problem is compounded when more loudspeakers are introduced.

3.2 Mono, Stereo and Surround Compatibility and the Control Room

To a (mono-eared) listener sat in the 'hot seat' in an anechoic chamber, equidistant from all loudspeakers, the panning problem will not occur; the timbre of a signal reproduced by a single loudspeaker will be the same as that reproduced simultaneously by many. In other words, the sound that is heard is the same as the electrical (voltage) summation of all of the signals fed to the loudspeakers. The correct pan-pot under these conditions is one that attenuates centrally-panned signals by 6dB between two loudspeakers, 12dB between four etc. This is *exactly* the pan-pot law required for correct fold-down from surround to stereo to mono, and is thus the correct one to use for television etc.

If the exercise is repeated in a non-anechoic room, use of the voltage summation pan-pot law will give rise to near-correct reproduction of panned low-frequency signals, but mid- and high-frequency signals will effectively reduce in level as more loudspeakers are operated. This phenomenon is very important when choices concerning recording studio control room acoustics are concerned.

An engineer working on a surround sound mix will tend to pan a sound first, and then apply any necessary equalisation, based on what is heard. If the control room is anechoic, the resultant mix will automatically fold down accurately to stereo and mono. However, if the control room is non-anechoic, the engineer will increase the mid- and high-frequencies of centrally panned sounds relative to sounds reproduced via a single loudspeaker, and the resultant mix will not fold down correctly; what is more, because the importance of mutual coupling depends upon the room acoustics, the mix will not travel well from one room to another. The mix from the anechoic control room will, of course, not sound correct in a semi-reverberant listening room, but at least there is a chance of correcting for the effects of mutual coupling by the listening room loudspeakers at the reproduction equipment end of the chain; something that would be impossible with the mix from the non-anechoic room. Clearly, the closer that the acoustics of a control room are to anechoic, the greater the chance that mixes from that studio will fold down correctly and travel successfully to other rooms – *including those of the consumer of the final product.*

In [4 & 5], Newell et al put forward the proposal that recording studio control rooms should be as acoustically 'non-environment' as possible; approaching the ideal of a (semi) anechoic room when possible. The arguments put forward in the present paper indicate that non-environment control rooms will become even more desirable when multi-channel reproduction becomes more commonplace.

3.3 The Use of a Third, Central Channel for Stereo and Surround Sound

If a third, central loudspeaker is introduced between a stereo pair, as is common for surround sound applications, the reproduction of centrally-panned signals in a non-anechoic room will differ considerably from those of the phantom image between the stereo pair; the sound from the central loudspeaker will contain more mid- and high-frequencies than the equivalent phantom image. Use of the voltage summation pan-pot (necessary for fold down to mono) results in consistent reproduction of fully-left, central and fully-right panned signals with a third central loudspeaker; however, this can put huge demands on the output capability of the central loudspeaker.

Most low frequency signals tend to be monaural (panned to centre), so with a voltage-summed panned signal, the centre-channel loudspeaker needs to be capable of radiating *four times* as much low frequency power as one of the stereo pair that it replaces if headroom is to be maintained. The increasingly common practice of using a powerful stereo pair of loudspeakers along with a smaller, less powerful central loudspeaker is clearly misguided and results in severe headroom problems with full-bandwidth, centrally-panned signals.

3.4 The Use of a Mono Sub-Woofer

For loudspeakers separated by a few metres, the power increase due to mutual coupling only occurs at low frequencies. The use of multiple 'satellite' loudspeakers for mid- and high-frequencies, along with a mono sub-woofer for low frequency reproduction removes the problem. However, mixes which use the voltage summation pan-pot law still gives rise to phantom images which are lower in level than those from single loudspeakers in semi-reverberant rooms, although the overall frequency balance should be preserved. It is for this reason that many mixing consoles use a -4½dB pan-pot law instead of the -6dB of voltage summation; the error in fold down from stereo to mono is then only 1½dB. It may also be argued that with some programme material, out-of-phase low frequency stereo information, which cannot be reproduced by a mono sub-woofer, can contribute to the feeling of ambience in live recordings or enhance special effects in film soundtracks etc.

4. CONCLUSIONS

In an earlier paper [1], mutual coupling between stereo loudspeaker pairs was shown to compromise the reproduction of phantom stereo images under most listening conditions. In this paper, the concept has been extended to include multi-channel loudspeaker systems such as used for surround sound. It is shown that mutual coupling is likely to be even more important for multi-channel systems than for stereo.

It is proposed that avoidance of mutual coupling problems in studio control rooms, by making them as anechoic as possible, permits the correct monitoring of voltage summation panned signals; voltage summation pan-pot laws are desirable if surround sound mixes are to fold down correctly to stereo and mono and are to successfully 'travel' from room to room.

5. REFERENCES

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[2] R F Allison, "The Influence of Room Boundaries on Loudspeaker Power Output", presented at the 48th Convention of the Audio Engineering Society, May 1974 in "Loudspeakers, an Anthology, Vol.1–Vol.25", edited by R E Cooke, The Audio Engineering Society, 1980, p353–59.

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